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PERFORMANCE OF ASYMMETRIC CODE-DESIGNED BUILDINGS FOR SERVICEABILITY AND ULTIMATE LIMIT STATES

A. M. CHANDLER[1*†] AND X. N. DUAN[2‡]

[1] *Department of Civil and Environmental Engineering, University College London, Gower Street, London WC1E 6BT, U.K.*
[2] *Ove Arup & Partners, 13 Fitzroy Street, London W1P 6BQ, U.K.*

SUMMARY

This paper addresses some key issues which have been the subject of dispute in recent years in studying the seismic torsional response of asymmetric structures. These issues include the interpretation of the code accidental torsional provision, and the influence of the force reduction factor and of the uncoupled lateral period, on the torsional response of asymmetric structures. The responses of single-storey torsionally unbalanced structural models, designed in accordance with the torsional provisions of seismic building codes in Europe, the United States and Canada, and subjected to seismic ground motions corresponding to both the serviceability and ultimate limit states, are studied analytically. On the basis of a better understanding of the above issues as achieved in this study, the performance of code-designed torsionally unbalanced structures for both limit states is assessed.

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KEY WORDS: earthquakes; torsion; response; elastic; inelastic

BACKGROUND AND INTRODUCTION

In the last five years, several detailed analytical studies have been carried out on the seismic inelastic response of code-designed systems, which have asymmetric distribution of stiffness and/or mass in plan.[1–10] Despite evidence arising from the considerable research effort applied world-wide to this problem, there is no universal agreement among researchers and code writers as to the understanding of seismic behaviour of asymmetric structures, and hence satisfactory criteria for deriving a solution to the design problem posed by torsion remain to be developed. A number of areas of controversy still exist. Reference 11 has summarized the key areas of concern, where the use of different definitions or the making of divergent assumptions has resulted in a lack of agreement among the results of researchers. To resolve these issues, it is imperative to co-ordinate international research efforts on this subject. With this in mind, a European Task Group (TG8) working under the auspices of the European Association for Earthquake Engineering was established in 1994. The primary purpose of TG8 is to focus on seismic torsional effects arising due to asymmetry of stiffness, mass or strength, or due to vertical irregularities such as geometric setbacks. It aims firstly to resolve, over a period of a few years, the key issues where controversies still exist and secondly to improve codified design procedures, in particular the torsional provisions of Eurocode 8.[12]

On the wider front, such issues must be satisfactorily resolved before results obtained from research can be implemented in developing an improved design methodology for seismic torsional response. Towards this

* Correspondence to: A. M. Chandler, Department of Civil and Environmental Engineering, University College London, Gower Street, London WC1E 6BT, U.K.
† Reader in Earthquake Engineering
‡ Seismic Engineer

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objective, this paper addresses some key issues raised in Reference 11. The responses of Torsionally Unbalanced (TU) structures, designed in accordance with the provisions of the 1993 edition of Eurocode 8[12] (EC8-93), the 1994 edition of the Uniform Building Code[13] (UBC-94), along with the 1995 edition of the National Building Code of Canada[14] (NBCC-95), for both the serviceability and ultimate limit states, have been studied analytically. These three codes incorporate archetypal static torsional provisions and have been carefully selected to test the effects of a range of lateral design strength distributions amongst the load-resisting elements of buildings. As such, they are particularly suitable for addressing the issues discussed in this paper.

Firstly, this paper addresses the key issue of how the codified accidental torsional provision (ATP) should be dealt with when evaluating torsional provisions. The purpose of introducing such a term in the design eccentricity expressions (as covered below) is to account for accidental effects which may give rise to torsional response but are not considered explicitly in determining element strengths. The inclusion or exclusion of code ATP in determining the strength distribution of TU structures and torsionally balanced (TB) reference structures when evaluating code torsional provisions has been an issue of some controversy. A number of discussions on this point have been published in the literature.[15–17] Based on results obtained in this study, the paper recommends a more logical and rational interpretation of code ATP.

Secondly, the need for code torsional provisions to cater explicitly for the differences in the serviceability limit state (SLS) design and the ultimate limit state (ULS) design is investigated. Presently, the differences between SLS design and ULS design are considered only in the lateral force provisions as code torsional provisions are not dependent on the limit state concerned. In the case of the ULS, code design eccentricity expressions are not dependent on the lateral force reduction factor, R. As a first step towards addressing this issue, Goel and Chopra[18] have proposed a dual-design approach, in which not only the design base shear force but also the coefficients used to determine the design eccentricity are defined differently for the two limit states. In the case of the ULS, Reference 18 recommended design eccentricity values which are dependent on the target ductility, which is equivalent to the force reduction factor, R. A more comprehensive parametric study is carried out in the present paper to investigate the effect of different limit states, and in the case of the ULS, the effect of the force reduction factor, on the seismic torsional response of TU structures.

Thirdly, the paper addresses the issue of period dependency in seismic torsional response. Tso and co-authors[4,5,9,10] along with Mittal and Jain[19] have deduced that the torsional effect is not period dependent and have therefore used only one period (generally 0·5 or 1·0 sec.) in their studies. On the other hand, the authors[1,7] along with Goel and Chopra[2,18] have regarded period as a key system parameter and have therefore presented results against this parameter. This issue is investigated further in the present paper.

Finally, to gain a more complete understanding of the above issues, in this study the performance of code designed TU structures for both limit states is evaluated. This evaluation identifies some of the shortcomings in current code torsional provisions and provides guidelines for developing an improved, optimized design approach for torsion, which is the subject of a companion paper.[20]

STRUCTURAL MODELLING CONSIDERATIONS

The TU structural model employed is an idealized single-storey, monosymmetric building model, as shown in Figure 1. It is similar to that adopted by most researchers of the problem. Although simple, it is sufficient to meet the objectives of the present study and it also enables comparisons with results obtained in other studies. The distribution of mass, stiffness and strength is assumed to be symmetric about the transverse x-axis but may be asymmetric about the lateral y-axis. The model consists of a rigid rectangular floor slab supported on three lateral load-resisting elements which are fixed, respectively, at the two edges and at the geometric centre of the floor slab. Transverse elements, which are oriented perpendicular to the direction of ground motion and parallel to the x-axis, are specifically excluded. This simplification is supported by a recent study[21] employing a single-storey model having resisting elements in both principal directions and subjected to bidirectional ground motion input. Reference 21 has concluded that provided the primary system parameters are identical, unidirectional analysis of TU systems, considering only the lateral load-

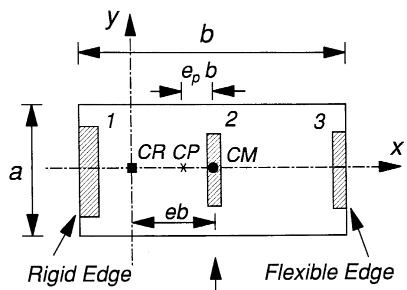


Figure 1. Plan view of the idealized single-storey torsionally unbalanced (TU) structural model

resisting elements and the corresponding unidirectional earthquake ground motion, gives valid and reasonably accurate results compared with those obtained by fully bidirectional analysis.

The mass is assumed to be uniformly distributed across the slab. Hence the Centre of Mass (CM) coincides with the slab's geometric centre. A representative value of 2·5 for the aspect ratio of the slab, b/a, is assumed. Since transverse elements are not included in the model, the aspect ratio of the slab is not a primary system parameter. The normalized (with respect to b) mass radius of gyration of the slab, ρ_m, is equal to 0·311. The Centre of Rigidity, (CR) is defined as the point in the plane of the slab through which a static force must be applied in order to induce only translation of the slab, without torsion. In the case of a single-storey model, CR coincides with the centre of stiffness, CS, which is defined as the point in the plane of the slab about which the first moment of the element lateral stiffnesses becomes zero. The distance between CM and CR is defined as the static eccentricity, e_s. In this study, this parameter is normalized with respect to the width of the building, b, resulting in a dimensionless system parameter, the normalized static eccentricity $e = e_s/b$. The torsional stiffness of the TU model about CR, K_θ, is equal to the second moment of stiffness about CR. The stiffness radius of gyration of the system, defined in Reference 4 as the square root of the ratio between K_θ and the total lateral stiffness K_y, determines the amount of lateral stiffness allocated to the two edge elements compared with that of the element at the centre. In this study, the former parameter is again normalized with respect to b, resulting in a dimensionless system parameter, the normalised stiffness radius of gyration ρ_k, defined as

$$\rho_k = \ = \frac{1}{b}\sqrt{\frac{K_\theta}{K_y}} \tag{1}$$

The distribution of lateral stiffness is determined by the two system parameters, e and ρ_k. The total lateral stiffness K_y is determined by another system parameter, the uncoupled lateral period T_y. Hence, the lateral stiffnesses of the three elements, k_i, $i = 1$, 2, and 3, are uniquely determined by three primary system parameters, e, ρ_k and T_y.

All three lateral load-resisting elements are assumed to have a bilinear hysteretic force–deformation relationship, with the post-yielding stiffness being 3 per cent of the initial elastic stiffness. Similar to the case of stiffness distribution, the first moment of strength determines the location of the centre of strength, CP, while the second moment of strength about CP determines the normalized strength radius of gyration, ρ_p. The distance between CM and CP defines the strength eccentricity, e_p. However, e_p and ρ_p are not primary system parameters. They are the results of structural analyses which determine the strength demand of each lateral load-resisting element. For the single-storey model, the seismic lateral load is the design base shear force applied through a point on the slab at a distance from CR equal to the design eccentricity, which is specified by code torsional provisions. The design base shear force is calculated based on the code design

spectra and is dependent on the system's uncoupled lateral period, T_y, and the force reduction factor, R. The latter is another primary system parameter.

In order to evaluate the effect of torsion in TU systems, it is desirable to compare responses of TU systems with those of a reference system which does not exhibit torsional response.[16] A TB reference system is employed in this study for this purpose. The TB reference model adopted in this study has stiffness distribution, total stiffness and mass inertia properties (total mass and mass moment of inertia about CM) identical to the TU system. The balance in torsion is achieved by relocating CM to coincide with CR. It can be physically achieved by firstly cutting the links between the slab and the load resisting elements and then moving the slab toward CR such that CM coincides with CR, and finally reconnecting the slab using massless rigid horizontal links if necessary. The strength distribution of the TB reference model is determined by a static analysis, applying the design base shear force through CR. Hence, the code ATP is excluded in determining the strength distribution of the TB system. As a result, the TB reference model is stiffness and strength proportional and responds only in translation in both the elastic and inelastic ranges. Hence, the TB system adopted in this study has the desired features as a reference system to evaluate torsional effects in TU systems.

There are four primary system parameters in this study, identified and defined above as T_y, e, R, and ρ_k. In order to examine the potential period dependency of torsional effects in TU systems, three values for T_y have been considered, namely T_y equal to 0·5, 1·0, and 2·5 sec. These values represent moderately short (hereafter referred to as short for brevity), intermediate and long-period structures, respectively. The value 0·5 sec. may be regarded as the upper bound of the short-period range. Since this period value has been employed repeatedly in References 4, 5, 9, 10 and other related studies, in order to obtain comparable results it has also been employed in this study to represent short-period structures. Three values for e have also been considered, namely $e = 0{\cdot}1$, 0·2, and 0·3, representing small, intermediate and large static eccentricities, respectively. In the case of the ULS, three values of the force reduction factor, namely $R = 1{\cdot}5$, 3·0, and 5·0, have been considered. These R-values represent, respectively, structures having low, intermediate and high ductility capacities. In the SLS, no force reduction is permitted, since structural members are expected to remain elastic under the relatively more frequent earthquake loads corresponding to the SLS. Hence, $R = 1{\cdot}0$ for the SLS. The range of ρ_k has been decided on consideration of the upper and lower bounds of this torsional stiffness parameter in realistic TU buildings. A ρ_k value smaller than the lower bound or larger than the upper bound will result in one of the lateral elements having negative stiffness. For the TU model considered in this study, the upper bound of ρ_k depends on e and is given by $\sqrt{0{\cdot}25 - e^2}$. Its lower bound is approximately 0·25. In this study, the lower bound (torsionally flexible systems) of ρ_k is fixed at 0·25, and its upper bound (torsionally stiff systems) is set to be 0·4 for $e = 0{\cdot}3$ and 0·45 for $e = 0{\cdot}1$ and 0·2. Both bounds of ρ_k will be increased if transverse elements are included. In their recent study, Tso and Wong[9] have shown that when ρ_k is larger than about 0·45 (systems having transverse elements), the responses of both edge elements are constant, being largely independent of changes in ρ_k. On this basis, results obtained in the present study at the upper bounds of ρ_k given above can be extended to systems having transverse elements and hence larger values of ρ_k.

The Newmark–Hall type of seismic design spectra, as illustrated in Figure 2, has been employed in this study to calculate the design base shear force. The peak horizontal ground acceleration (PGA) corresponding to the ULS is assumed to be $0{\cdot}3g$, representing strong ground motion. The corner (or control) periods of the spectrum are decided based on rock or stiff soil site conditions. The relationship between the design spectra for the SLS and the ULS varies from region to region, depending on the regional seismicity and the associated risk levels decided by code drafting authorities. Reviewing the seismic codes in New Zealand[22] (NZS4203: 1992), the United States[13] (UBC-94), Japan[23] (BCJ-1991) and China[24] (GBJ11-89), it is determined that the ratio between the design spectra for the SLS and the ULS ranges between one-sixth to one-fourth, with the average being one-fifth. In this study, a value of one-fifth is therefore considered to be a representative value and hence the PGA for the SLS has been taken as $0{\cdot}06g$. As shown in Figure 2, a single shape of design spectra for both the ULS and the SLS is employed in this study. This practice is common in

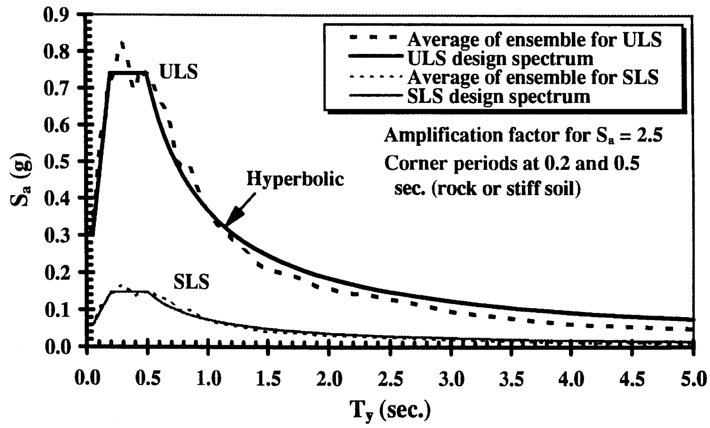


Figure 2. Design and response spectra for the serviceability limit state (SLS) and the ultimate limit state (ULS)

building codes, such as those of Japan, New Zealand and China. It should be noted that EC8-93,[12] UBC-94,[13] and NBCC-95,[14] specify one design spectrum for the ULS only. Designers are not required by these three codes to check explicitly that the requirements of the SLS are satisfied.

In order to minimize the dependency of the response of both the TU and TB systems on the characteristics of individual earthquake records, a carefully selected ensemble of eight earthquake records from North America and Europe has been employed as the ground motion input. These records are taken from rock or stiff soil sites, with ratios of the peak ground acceleration to peak ground velocity close to 1·0 g/(m/s). The average 5 per cent damped elastic response spectra of this ensemble of records, scaled to a common peak ground acceleration of $0{\cdot}3g$ for the ULS and $0{\cdot}06g$ for the SLS, closely match the employed design spectra for the ULS and SLS, as shown in Figure 2. The selected records and related parameters have been listed in Table 4 of Reference 11.

Results of dynamic earthquake response analyses will be presented in a statistical manner in terms of the average responses corresponding to the ensemble of selected earthquake records. The standard deviations of the response parameters are small, ranging from one-tenth to one-third of the average values, and hence are not presented herein. The average displacement ductility demand (henceforth referred to as DD) and the ratio between the DD of an element in the TU system and that of the corresponding element in the TB reference system, Γ_{DD}, are employed as response parameters. If the DD's of elements in the TU system are lower than or in the neighbourhood of the DD's of the TB reference system, that is if Γ_{DD} is lower than or in the neighbourhood of unity, then the response of the TU system is considered to be satisfactory. The neighbourhood of unity may be quantitatively defined as a margin of 10 per cent at either side of unity. If Γ_{DD} is larger than 1·1, then the response of the TU system is considered unacceptable. In this paper, only the DD's and Γ_{DD}'s corresponding to the two edge elements, namely elements 1 and 3, are presented. Those corresponding to the element at the centre, namely element 2, of the TU system are lower than the values of the TB reference system and are not sensitive to changes of system parameters, and are therefore not presented. Another important response parameter is the element peak displacement ratio, Γ_{Δ}, defined as the ratio between the peak displacement of an element in the TU system and that of the corresponding element in the TB system. However, it is not necessary to adopt Γ_{Δ} as an independent response parameter, since Γ_{Δ} and Γ_{DD} are related[9] as follows:

$$\Gamma_{\Delta} = \Gamma \Gamma_{\mathrm{DD}} \tag{2}$$

in which Γ is the element strength ratio as discussed in detail in the following section.

Table I. Design eccentricity coefficients in eqn.'s (3) and (4)

Code	α	γ
EC8-93[12]	$1{\cdot}0 + e_0/e$	1·0
UBC-94[13]	1·0	1·0
NBCC-95[14]	1·5	0·5

Note: The additional eccentricity e_0 in EC8-93 is equal to the smaller of the following two values[12]

$$e_0 = 0{\cdot}1(1 + a/b)\sqrt{10\,e} \leqslant 0{\cdot}1\,(a+b)$$

or

$$e_0 = \frac{1}{2e}\left[(\rho_m^2 - e^2 - \rho_k^2) + \sqrt{(\rho_m^2 + e^2 - \rho_k^2)^2 + 4e^2\rho_k^2}\right]$$

Table II. Values of coefficients defining code accidental provision

Code	β	β_1	β_2
EC8-93[12]	0·05	0·0	0·05
UBC-94[13]	$0{\cdot}05A_x$	$0{\cdot}05(A_x - 1)$	0·05
NBCC-95[14]	0·1	0·05	0·05

Note: The amplification factor A_x in UBC-94 is determined from the following formula

$$A_x = \left[\frac{\delta_{\max}}{1{\cdot}2\,\delta_{\text{avg}}}\right]^2 \leqslant 3{\cdot}0$$

where $\delta_{\max}$ and δ_{avg} are the maximum and the average displacements, respectively, when a lateral force is applied to the slab at a distance equal to $0{\cdot}05b$ from CM

STRENGTH DISTRIBUTIONS FOR TORSIONAL DESIGN

The design base shear force is determined from the design spectra, as shown in Figure 2, depending on the system parameters T_y and R in the case of the ULS and on T_y only in the case of the SLS. The approach adopted for determining the strength distribution of the TB reference system has been described in the previous section. For the TU system, the distribution of strength is determined by carrying out static structural analyses, with the lateral load being the design base shear force applied through a point on the slab at distances from CR (towards CM) equal to the design eccentricities specified by code torsional provisions. As stated earlier, the torsional provisions from three leading building codes, UBC-94, NBCC-95 and EC8-93, have been considered in specifying the strength distributions in TU systems. For each element, the more unfavourable strength demand resulting from applying the two design eccentricities is used for sizing the element considered. The normalized (with respect to the width of the building, b) design eccentricities, e_{d1} and e_{d2}, are specified in codes as follows:

$$e_{d1} = \alpha e + \beta \tag{3}$$

$$e_{d2} = \gamma e - \beta \tag{4}$$

The codified values for the coefficients, α, γ and β are given in Tables I and II. The term β is called the code ATP, as previously discussed. A view adopted in some previous analytical studies is that since accidental torsional effects are difficult to quantify and are not simulated in analytical studies, the allowances given in code torsional provisions to account for them, namely β, should not be included (so effectively β is taken as zero) in determining strength distribution in either the TU or the TB models. This approach has been previously adopted by the authors,[1,7] Goel and Chopra,[2,18] and De Stefano *et al.*[6] and will again be considered (as Case 1 of two alternative approaches) in this study. However, another view states that code provisions should be taken and assessed in their entirety because they will be applied in their entirety in practice. This view is further supported by the argument that the unconservatism of one part (αe or γe) may be compensated by the overconservatism of the other (code ATP, β). This approach has been adopted by Tso and co-authors.[4,5,9,10] One shortcoming of this approach is its inability to simulate the accidental effects in analytical studies. Another shortcoming is its inconsistency in applying code torsional provisions in their entirety to both TU and TB models. Tso and co-authors have included β in determining strength distributions of TU systems but have excluded β for TB systems. Strictly, however, according to their

arguments, β should also be included for TB systems since in practice the code provisions will be applied in their entirety for TB systems as well as for TU systems.

In order to overcome the inconsistency mentioned above, other studies[8,15] have proposed that code torsional provisions be taken and applied in their entirety for both TU and TB systems. However, this approach has a major shortcoming in that the TB reference system itself responds torsionally in the inelastic range (see Reference 16), making it difficult to quantify torsional effects in TU systems.

The argument that a part of the potentially overconservative second term in equations (3) and (4), namely, β, may compensate for any unconservatism of the first term in these equations, is worth further consideration. This approach has been implemented in the NBCC[14] since 1985, when the value of β was increased from 0·05 to 0·1. One reason for this increase was to compensate for the unconservatism of the torsional provision of the 1980 edition of NBCC, as outlined by Tso.[25] A critical question arises which is concerned with setting an appropriate codified allowance to account for the combined effects from all accidental sources. Once this amount is established, the remainder in β, if any, could be viewed as a compensation for the possible unconservatism of the first term in equations (3) and (4). Recent studies by De la Llera and Chopra[26,27] have concluded that in the case of elastic response, the estimated increase in edge displacement by an allowance (within β) of 0·05 has a 30 per cent probability of being exceeded by the combined torsional effects due to all accidental sources. In the case of inelastic response, Pekau and Guimond[28] have concluded that an allowance of 0·1 becomes necessary to account for uncertainties in strength distribution and unbalanced stiffness degradation in the post-yielding behaviour of resisting elements.

In order to accommodate the above argument, a second approach (termed Case 2) has been employed here to deal with code ATP. In Case 2, an allowance of 0·05 (termed β_2, where $\beta = \beta_1 + \beta_2$) is allocated to account for unfavourable accidental torsional effects and hence since these effects are not modelled analytically, this allowance is not included in determining strength distributions of elements in either the TU or the TB model. A value of 0·05 is selected for β_2 in this study since this value is employed in the design eccentricity expressions by EC8-93, UBC-94 for regular structures, and also the 1980 edition of the NBCC to account for accidental torsional effects. It should be noted that, as pointed out by Pekau and Guimond,[28] a value larger than 0·05 may become necessary when uncertainties regarding a structures's inelastic behaviour should be considered. For each code, the remainder of β, if any (β_1), is included in determining the strength distributions of the TU model but not for the TB model. For defining this approach, equations (3) and (4) can be re-defined as follows:

$$e_{d1} = [\alpha e + \beta_1] + \beta_2 \tag{5}$$

$$e_{d2} = [\gamma e - \beta_1] - \beta_2 \tag{6}$$

Table II gives a summary of values for β_1 and β_2 adopted in the above approach. It should be noted that β_2 is the allowance allocated specifically to account for accidental torsional effects and is therefore omitted in this study. To summarize, therefore, in Case 1 the codified ATP's have been fully omitted in determining element strengths in both TU and TB models. In Case 2, partial inclusion of the ATP (β_1, Table II) has been made, for the TU model only, to simulate the apparent intention of certain codes (such as UBC-94 and NBCC-95) to allow part of the ATP to compensate for the potential non-conservatism in the remaining part of the design eccentricity expressions.

Figure 3 shows the element strength ratio, Γ, defined as the ratio between the strength of an element of the TU system and that of the corresponding element of the TB system, as functions of ρ_k and e. Strength ratios for both the flexible edge element (element 3) and the stiff edge element (element 1) are shown for all three codes considered. For element 3, the strength ratio is governed by e_{d1} [equations (3) and (5)] and is always larger than unity, implying an increase in strength for element 3 due to code torsional provisions. The amount of increase is the largest in the case of EC8-93, and smallest in the case of UBC-94. For all three codes, the ratio decreases with increasing ρ_k and with decreasing e. For element 1, the strength ratio is usually governed by e_{d2} [equations (4) and (6)] except in the case of EC8-93 when ρ_k is small, in which case e_{d1} governs the strength of this element. Element 1 strength ratios are always lower than or equal to unity. Values

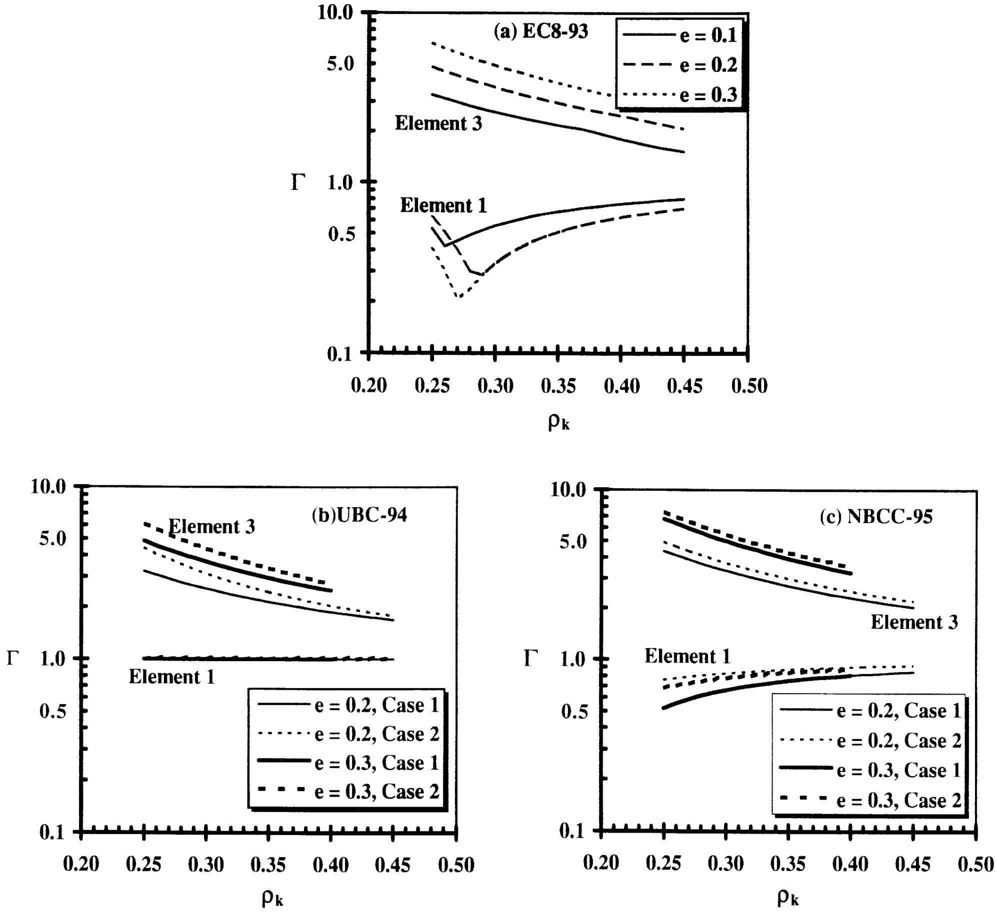


Figure 3. Element strength ratios (TU/TB)

lower than unity in the case of NBCC-95 and EC8-93 indicate a decrease in strength of element 1 permitted by these two codes, taking into account the supposed beneficial effects of torsion. In contrast, UBC-94 does not allow any beneficial effects due to torsion to be considered in design. Hence, element 1 strength ratios corresponding to UBC-94 are equal to unity, being independent of ρ_k, e and the approach employed to deal with code ATP [Figure 3(b)]. The difference between the design strengths of element 3 corresponding to NBCC-95 [Figure 3(c)] and resulting from the two cases of dealing with the code ATP is insignificant, remaining small across the full range of ρ_k. It can also be noted that the difference between the design strengths of element 3 corresponding to UBC-94 [Figure 3(b)] as well as of element 1 corresponding to NBCC-95 [Figure 3(c)], resulting from the two cases of dealing with the code ATP, is significant only when ρ_k is small, being reduced rapidly with the increase in ρ_k and becoming insignificant for systems with intermediate and large values of ρ_k.

The overstrength factor, defined as the ratio between the total lateral strength of the TU system and that of the TB system, is shown in Figure 4 as a function of ρ_k. The overstrength factor is always larger than unity, the consequence of adopting the more unfavourable strength demand for each element resulting from the two design eccentricity expressions. EC8-93 results in the lowest overstrength factor, except for systems with $e = 0{\cdot}2$ and ρ_k near the lower bound. The two approaches for dealing with code ATP do not lead to significantly different overstrength factors, and the difference reduces with increasing ρ_k.

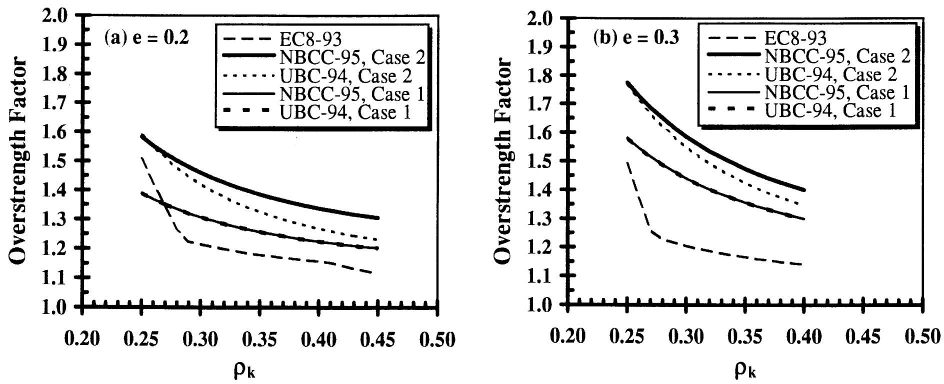


Figure 4. Overstrength factors for systems with moderate ($e = 0{\cdot}2$) and large ($e = 0{\cdot}3$) static eccentricity

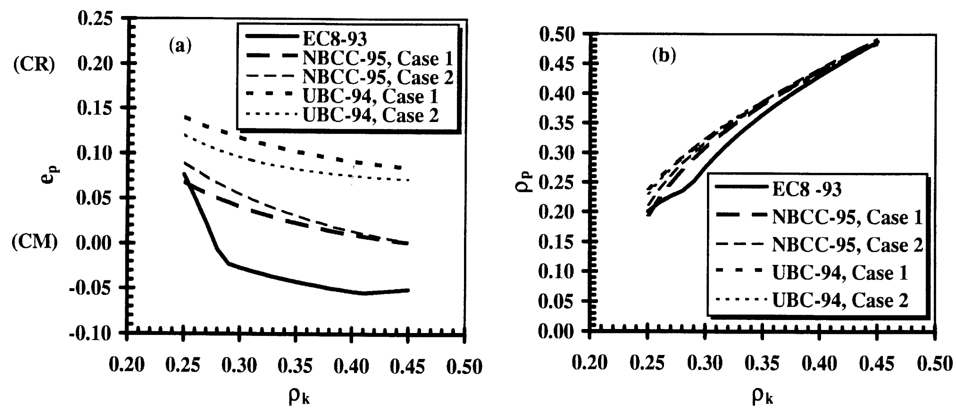


Figure 5. Normalized strength eccentricity (a) and normalised strength radius of gyration (b) for systems with a moderate ($e = 0{\cdot}2$) static eccentricity

Figure 5(a) shows the normalized strength eccentricity, e_p, as a function of ρ_k for systems with moderate static eccentricity, $e = 0{\cdot}2$. A positive value of e_p implies that the centre of strength, CP, is located to the left of CM in Figure 1 (that is towards CR), while a negative e_p implies that CP is located to the right of CM (away from CR). A TU system designed in accordance with EC8-93 will have its CP close to CM and located to the right of CM, except for systems with very small ρ_k values [Figure 5(a)]. NBCC-95 leads to CP being located close to CM and to the left of CM. Among the three codes considered, UBC-94 results in CP to be located closest to CR, being about mid-way between CR and CM. It can again be observed that the location of CP is not significantly influenced by the difference in dealing with the code ATP in Cases 1 and 2. Results corresponding to systems with a small ($e = 0{\cdot}1$) or a large ($e = 0{\cdot}3$) static eccentricity show similar trends with respect to e_p, and hence are not presented.

Figure 5(b) presents the normalized strength radius of gyration, ρ_p, which quantifies the second moment of strength distribution, as a function of ρ_k for systems having a moderate static eccentricity $e = 0{\cdot}2$. Results corresponding to systems having a small ($e = 0{\cdot}1$) or a large ($e = 0{\cdot}3$) static eccentricity have been found to show similar trends. Among the three codes considered, EC8-93 allocates the largest proportion of the total strength to the element at the geometric centre of the slab, element 2, hence leading to slightly lower values of ρ_p. NBCC-95 and UBC-94 result in almost identical values of ρ_p. Values of ρ_p are not influenced notably by the difference in dealing with the code ATP.

EFFECT OF DIFFERENT INTERPRETATIONS OF CODE ATP

This section evaluates the effect on the seismic torsional response of TU systems of adopting different interpretations of code ATP when determining the element strength distributions. The dynamic response time histories of both TU and TB systems subjected to the selected ensemble of earthquake records, scaled in accordance with ULS and SLS ground motion parameters, have been obtained by numerical integration. The central difference method has been used for the step-by-step time-history analysis. The time increment of the numerical integration has been selected to be 1/30th of the shorter elastic modal period of a given system. The viscous damping for both modes is assumed to be 5 per cent of critical damping. A Rayleigh damping matrix has been obtained by assuming that the damping matrix is proportional to both the mass and the initial elastic stiffness matrices.

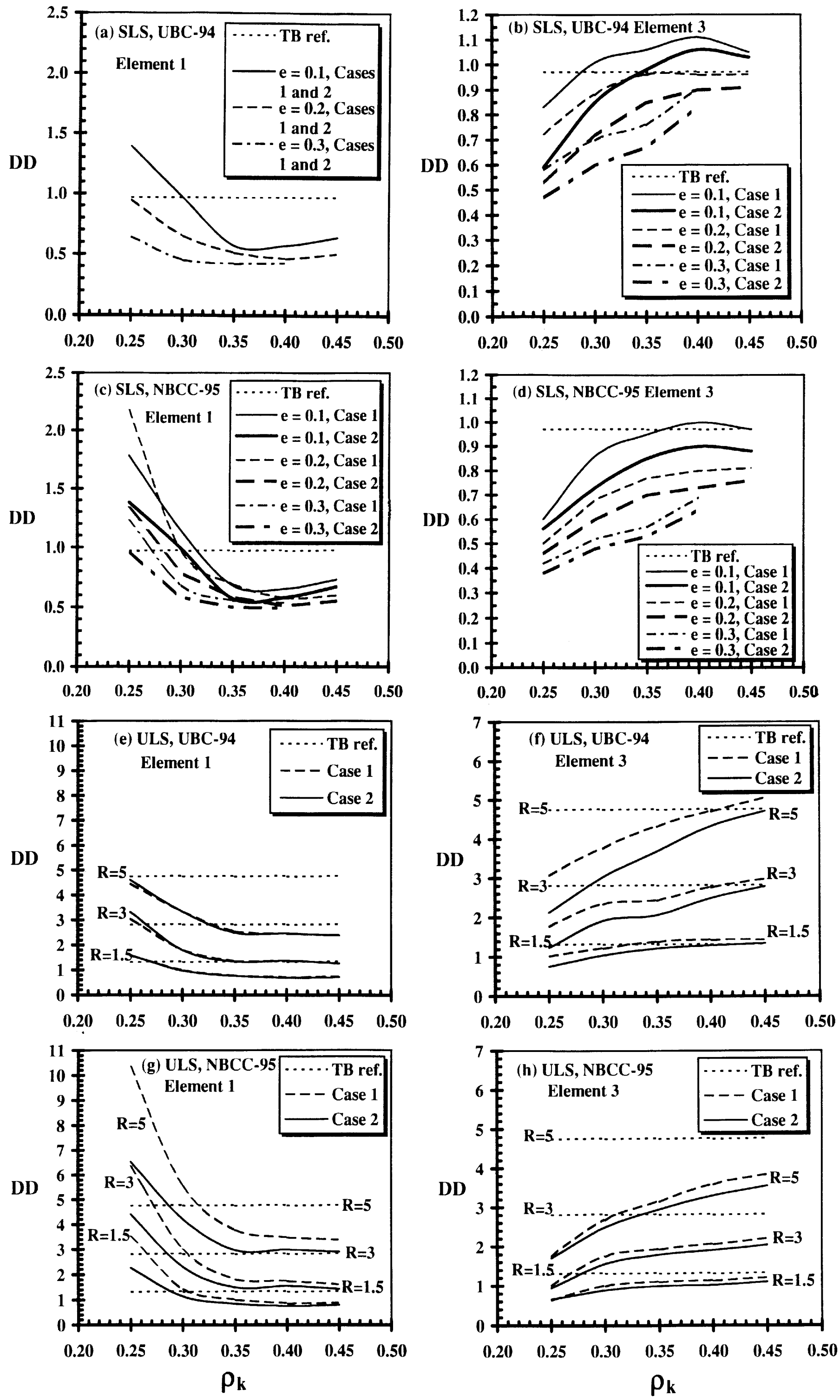
Figure 6 shows the DD's for the SLS (upper four parts) and the ULS (lower four parts) corresponding to the two interpretations of code ATP in UBC-94 and NBCC-95. The results shown are for $T_y = 0{\cdot}5$ sec only. Results corresponding to $T_y = 1{\cdot}0$ sec and $T_y = 2{\cdot}5$ sec, which are not shown in this paper for brevity, show identical trends. It can be seen from Figure 6 that in TU systems designed in accordance with UBC-94 the response of element 1 remains almost unchanged for the two cases of dealing with the code ATP, whilst the response of element 3 differs between the two cases. However, the difference in element 3 response is significant only when ρ_k is small (torsionally flexible systems), being rapidly reduced when ρ_k increases. In contrast, analysis of TU systems designed in accordance with NBCC-95 shows that the element 3 response is relatively insensitive to the differences in the two cases of dealing with the code ATP, while element 1 response differs significantly between the two cases. Again, the difference is significant only when ρ_k is small. These observations are the direct consequence of, and can be fully explained by, the element strength ratios for these codes, shown in Figure 3. Despite the above-observed differences in the DD's for torsionally flexible systems, the DD's corresponding to the two cases of the TU system in fact lead to the same conclusions as to the conservatism, or otherwise unconservatism, of the various code torsional provisions in determining the strength demand of the edge elements, when compared with the DD's of the corresponding TB reference system. Hence, the use of only one approach of dealing with the code ATP is considered sufficient for the following sections of this study.

Between the two approaches of interpreting the code ATP, the second approach (Case 2) offers the more logical interpretation of the code ATP. Firstly, as in Case 1, it is consistent with the evaluation procedure, since the inability of simulating the accidental torsional effects in the evaluation procedure has been taken into account. Secondly, it has accommodated the view that the potential overconservatism of the code ATP may compensate for the possible unconservatism of the first term in the design eccentricity expressions. This advantage is particularly important when applying the torsional provisions of UBC-94, in which the effect of the system parameter ρ_k is taken into account by multiplying the code ATP ($0{\cdot}05b$) by an amplification factor A_x. The smaller the ρ_k, the larger the A_x. Hence, part $[0{\cdot}05b(A_x - 1)]$ of the UBC-94 code ATP ($0{\cdot}05bA_x$) is meant to compensate, in torsionally flexible systems, for the apparently nonconservative first term in the design eccentricity expressions and as such should be included in determining strength distributions of TU systems when UBC-94 is applied (see Reference 9 for a more extensive discussion of this point). Therefore, the second approach (Case 2) will be adopted throughout the remaining sections of this paper.

EFFECT OF THE FORCE REDUCTION FACTOR

The force reduction factor, R, determines the degree to which the TU and TB systems are loaded into the inelastic range. Only a few studies have examined its influence on the ULS performance of TU systems. Goel

Figure 6. Effect of different interpretations of the code accidental torsional provisions on the SLS and ULS performance of short period ($T_y = 0{\cdot}5$ sec) TU systems


(a) SLS, UBC-94
Element 1
TB ref.
e = 0.1, Cases 1 and 2
e = 0.2, Cases 1 and 2
e = 0.3, Cases 1 and 2
(b) SLS, UBC-94 Element 3
TB ref.
e = 0.1, Case 1
e = 0.1, Case 2
e = 0.2, Case 1
e = 0.2, Case 2
e = 0.3, Case 1
e = 0.3, Case 2
(c) SLS, NBCC-95
Element 1
(d) SLS, NBCC-95 Element 3
(e) ULS, UBC-94
Element 1
TB ref.
Case 1
Case 2
R=5
R=3
R=1.5
(f) ULS, UBC-94
Element 3
(g) ULS, NBCC-95
Element 1
(h) ULS, NBCC-95
Element 3
DD
ρk

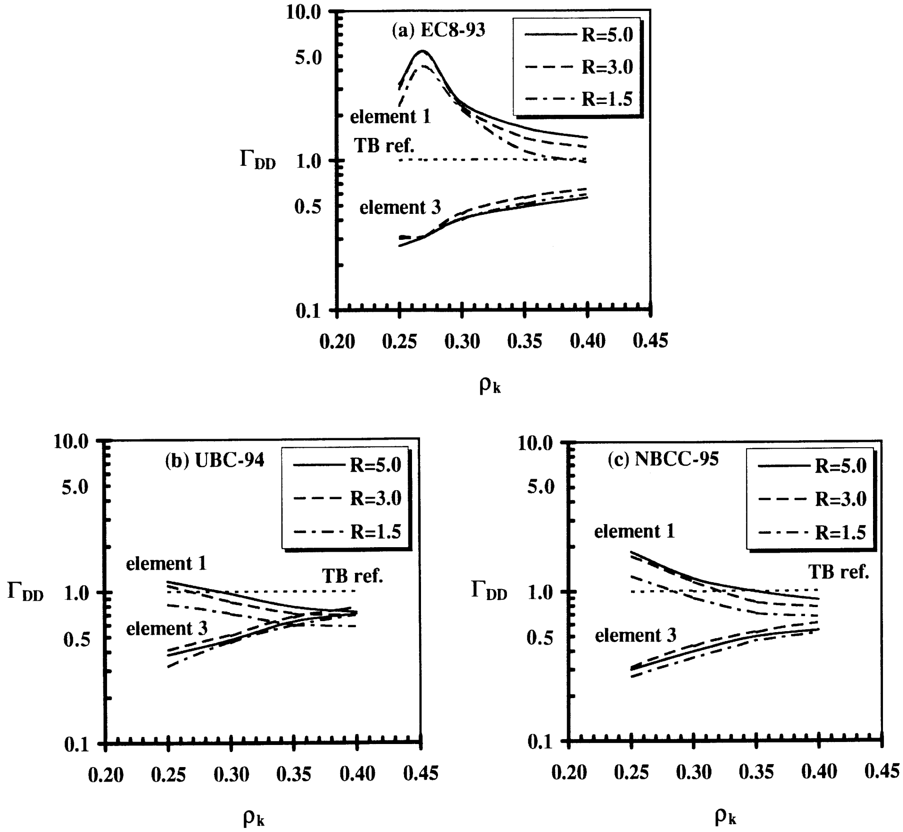


Figure 7. Influence of the force reduction factor on the ULS performance of TU systems, $T_y = 2{\cdot}5$ sec, $e = 0{\cdot}3$

and Chopra[18] have concluded that when the force reduction factor increases, namely when the TU system is excited more and more into the inelastic range, the torsional deformation decreases. Hence, TU systems behave increasingly like inelastic single-degree-of-freedom (SDOF) systems when R increases. This conclusion supports findings made in an earlier study by Kan and Chopra.[29] However, little attention has been paid to the influence of R on the DD and the ratio Γ_{DD} arising in the edge elements in TU systems.

Figure 7 presents Γ_{DD} for both elements 1 and 3 of TU systems designed in accordance with all three codes here considered. These illustrative results correspond to $T_y = 2{\cdot}5$ sec and $e = 0{\cdot}3$. It can be seen that R has little effect on the ratio Γ_{DD} for element 3. However, for element 1, Γ_{DD} is very significantly influenced by R. For this stiff edge element, Γ_{DD} increases with increasing R, suggesting that when the TU system is excited more and more into the inelastic range, the performance of element 1 becomes more and more unfavourable. At this stage, it is enlightening to examine the element peak displacement ratio Γ_{Δ}. In Equation (2), Γ is independent of R, hence, Γ_{Δ} of element 1 also increases with increasing R, in the same proportion as Γ_{DD}. Since torsional rotation of the floor slab reduces the peak displacement of element 1, Γ_{Δ} of element 1 is always smaller than unity. Therefore, an increasing Γ_{Δ} of element 1 implies that the displacement response of element 1 becomes increasingly close to that of the TB system. This observation in turn suggests that the peak torsional displacement of the floor slab decreases and that the peak translational displacement of the floor slab in TU systems, divided by that of the TB system, increases with increasing R. Therefore, when R increases, a TU system behaves increasingly like an inelastic SDOF system, exhibiting decreased torsional deformation and increased translational deformation. The approximate

cancellation of these two effects explains why the Γ_{DD} and hence Γ_{Δ} of element 3 remain little changed when R changes.

The above finding made in this study is consistent with that of Kan and Chopra[29] and Goel and Chopra.[18] Since R has a significant influence on the performance of element 1, which for the codes considered is the critical element because in many cases Γ_{DD} of element 1 is larger than unity (Figure 7), its influence should be considered in an improved and optimised approach for strength distribution in TU systems. This broader issue is the subject of the companion study.[20]

PERIOD DEPENDENCY

In previous studies,[1,7,8] the authors have found that the response of TU systems is significantly dependent on the uncoupled lateral period, T_y. The response of element 1 tends to be larger, and that of element 3 smaller, in long period systems when compared with short period systems. These findings are again confirmed by results presented in Figure 8, which illustrates the period dependency of both the SLS and the ULS performance of edge elements 1 and 3, in code-designed TU systems. These presented results correspond to the representative case of $e = 0{\cdot}2$, and $R = 5{\cdot}0$ (ULS). It can be seen that T_y influences the response of element 1 much more significantly than it influences the response of element 3. The response of element 1 in long-period ($T_y = 2{\cdot}5$ sec) TU systems is always substantially larger than its counterpart in short-period ($T_y = 0{\cdot}5$ sec) TU systems. For long-period TU systems, all codes lead to poor performance of element 1 in the SLS, as well as the ULS, when ρ_k is small or moderate. In contrast, the response of element 3 in long-period systems is always somewhat lower than its counterpart in short period TU systems. The results corresponding to intermediate period ($T_y = 1{\cdot}0$ sec) TU systems are sometimes close to those of long-period systems and sometimes close to those of short-period systems. It is apparent that an evaluation of code torsional provisions based on short-period systems ($T_y = 0{\cdot}5$ sec) only[4,5,9,10] will draw unconservative conclusions with respect to the performance of element 1. Hence, period dependency in the performance of TU systems should be taken into account in evaluating code torsional provisions as well as in developing an optimised, improved design procedure for determining strength distributions of TU systems, as fully discussed in the companion paper.[20]

Recalling equation (2), it may also be concluded that the peak displacement ratio, Γ_{Δ}, of element 1 is always larger in long period TU systems than its counterpart in short period TU systems. On the other hand, Γ_{Δ} of element 3 in long period TU systems is always smaller than its counterpart in short-period TU systems. Given the fact that due to torsion, Γ_{Δ} of element 3 is always larger than unity and that Γ_{Δ} of element 1 is always smaller than unity, one will further conclude that the peak displacements of both edge elements in long period TU systems are closer to the peak displacements of the corresponding TB reference systems. Therefore, long-period TU systems tend to respond more in translation and less in torsion. It should be noted that unlike in Reference 8, conclusions drawn in this section are not influenced by torsion in the TB reference model, which due to balanced stiffness and strength distributions does not respond torsionally. Hence, the presented results reveal genuine period-dependent effects.

PERFORMANCE OF CODE-DESIGNED TU BUILDINGS FOR SERVICEABILITY AND ULTIMATE LIMIT STATES

This section assesses the performance of code-designed TU buildings for both the SLS and the ULS. Results presented in previous sections have shown that element 1 is the critical element, since the DD of element 1 is often larger than the DD of the corresponding TB reference building. The performance of element 3 is generally satisfactory. The DD of element 3 is lower than the DD of the corresponding TB reference building, due to the increased allocation of strength by code torsional provisions. Hence, the performance of element 1 is of primary concern in assessing the performance of TU buildings. It has been shown in the previous section that the displacement ductility ratio, Γ_{DD}, of element 1 is significantly larger in long period TU

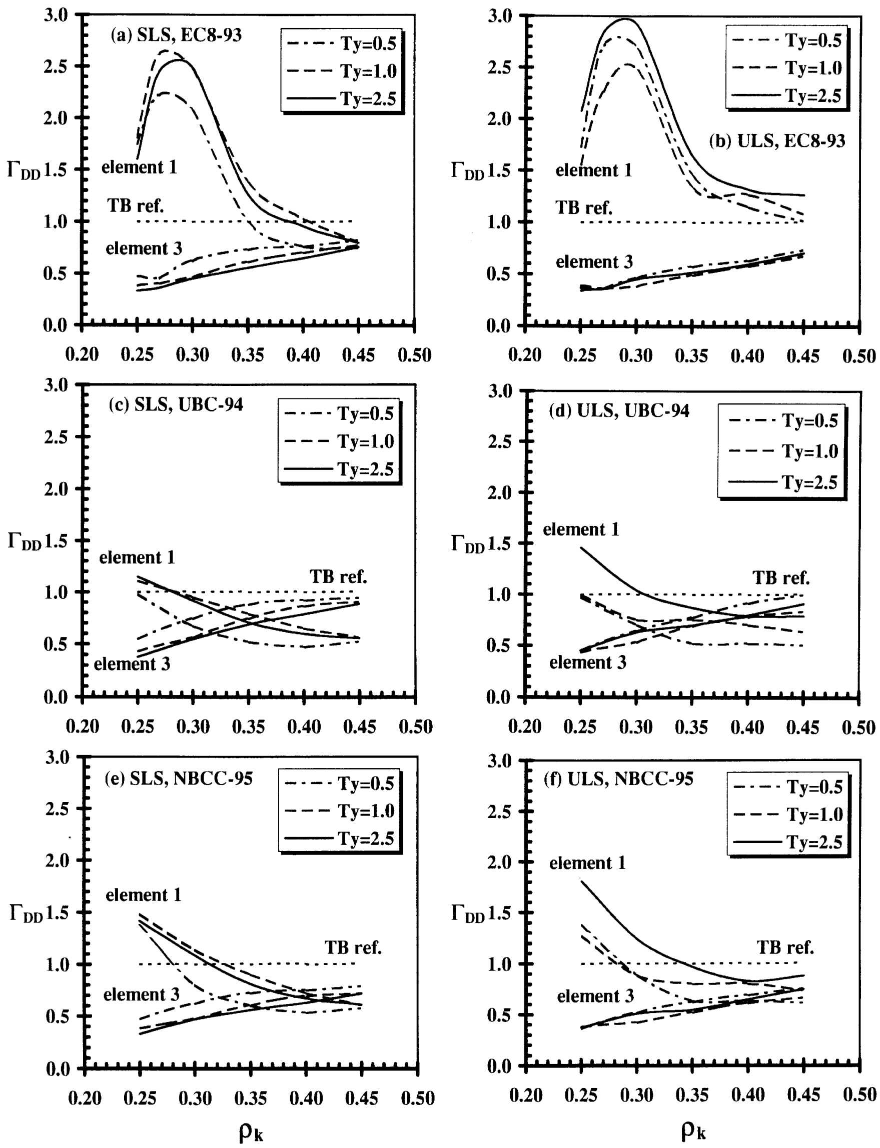


Figure 8. Influence of the uncoupled lateral period on the SLS and ULS performance of TU systems with $e = 0{\cdot}2$; $R = 5{\cdot}0$ in the case of the ULS.

buildings than in short period TU buildings. Hence, for brevity, only the DD's in long-period ($T_y = 2{\cdot}5$ sec) TU and TB systems (where Γ_{DD} is the ratio of DD's for the two systems) will be presented in this section.

Performance of TB reference models

The DD's in short- and intermediate-period TB reference models are approximately equal to, but slightly lower than, the force reduction factor, R, in the case of the ULS, and are approximately equal to unity in the case of the SLS. In long-period TB models (see Figures 9 and 10), the DD's are significantly lower than R in the case of the ULS and lower than unity in the case of the SLS. These results can be explained by examining the design spectrum and the average response spectrum shown in Figure 2. It can be seen that the two spectra

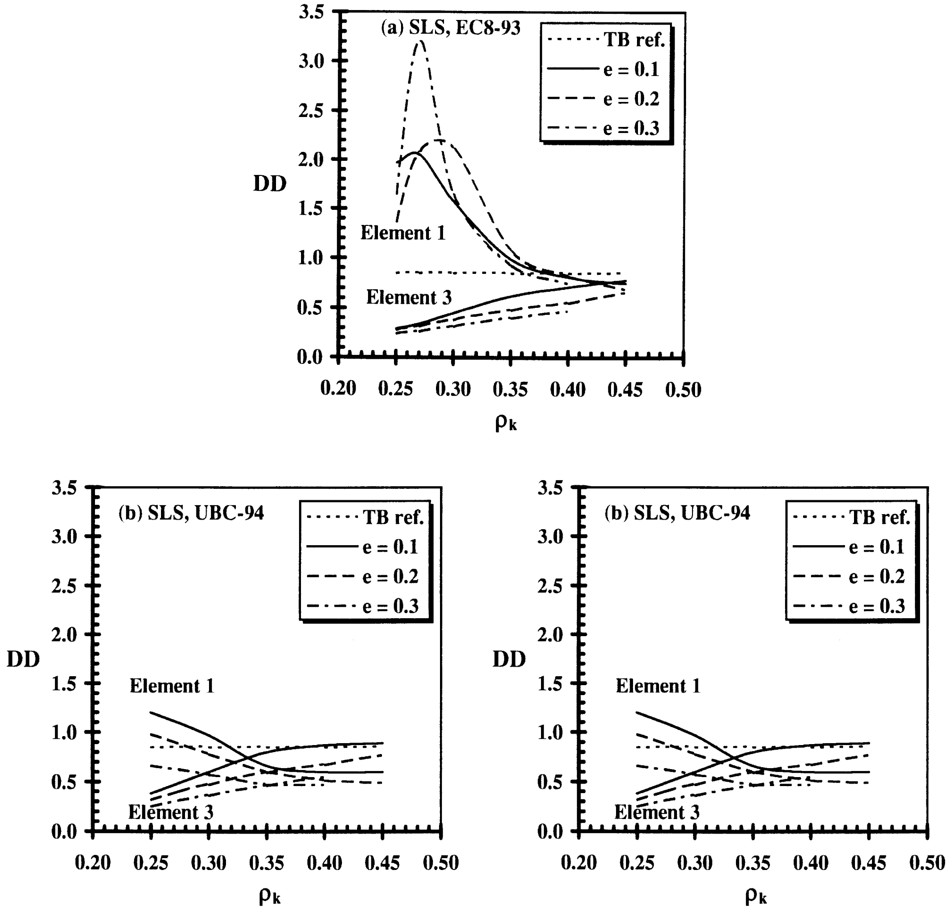


Figure 9. Performance of long-period ($T_y = 2{\cdot}5$ sec) TB and TU systems in the SLS

match each other very closely at periods 0·5 and 1·0 sec. However, at long periods, the match between the two spectra is less close, with the design spectrum being higher than the average response spectrum. It should be noted that the above-mentioned differences have no effect on the element strength distributions in either the TB or the TU models.

Performance of code-designed TU buildings

The DD's of TU buildings designed in accordance with all three codes considered in this study are presented in Figures 9 and 10 for the SLS and the ULS, respectively. The variation of DD's as functions of ρ_k follow the reverse trends in the variations of Γ, as shown in Figure 3. When ρ_k becomes larger, approaching its upper bound, both the DD and Γ curves become approximately constant, signalling that when the TU system becomes torsionally stiff, its strength distribution and its response approach those of the TB reference system. Results obtained by Tso and Wong[9] have confirmed that this trend extends to torsionally very stiff systems having transverse resisting elements. Hence, results obtained in the present study apply equally well for torsionally very stiff TU systems having ρ_k values higher than the upper bound obtainable in the three element TU model adopted herein.

1. SLS performance (Figure 9). The DD of element 3 in TU models is generally lower than that of the TB

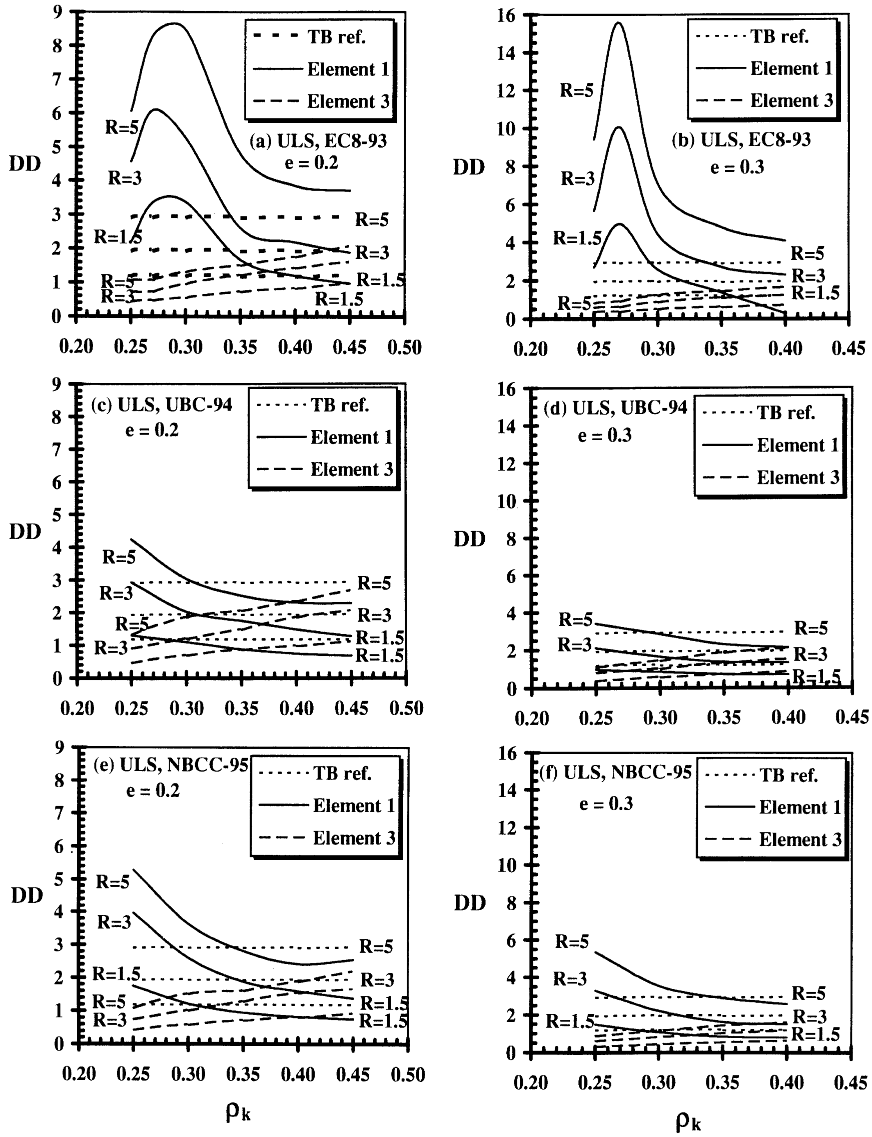


Figure 10. Performance of long-period ($T_y = 2{\cdot}5$ sec) TB and TU systems in the ULS

reference system for all three codes. The former may exceed the latter only in the case of UBC-94 when *e* is small and ρ_k is moderate to large, particularly in short-period TU structures [see Figure 6(b)]. It is clear that NBCC-95 and EC8-93 are overly conservative in estimating the strength demand of element 3, particularly for torsionally flexible systems.

Element 1 is the critical element for all three codes. EC8-93 leads to very poor performance of this element at small to moderate ρ_k values, with SLS DD's in the range 2–3 [Figure 9(a)]. NBCC-95 and UBC-94 are slightly unconservative at small ρ_k values, for systems with small to moderate *e*. For the latter two codes, the performance of element 1 is satisfactory when *e* is large. This can be explained by the large overstrength factors associated with these two codes when *e* is large, as shown in Figure 4. At large ρ_k values (torsionally

stiff systems), all three codes result in a lower DD of element 1 than that of the TB reference model. UBC-94 and NBCC-95 appear to be overly conservative for element 1 when ρ_k is large.

2. ULS performance (Figure 10). The DD's of element 3 in TU models are generally lower than those of the TB system. All three codes are conservative, and often overconservative, in estimating the strength demand of element 3 for all three considered force reduction factor values, $R = 1{\cdot}5$, $3{\cdot}0$ and $5{\cdot}0$. The degree of overconservatism increases as ρ_k decreases (torsionally flexible systems) and as R and e increase. Hence all three codes are conservative for element 3 when e is large or ρ_k is small. In general, therefore, too much strength has been allocated to element 3 in accounting for the unfavourable effect of torsion in ULS (inelastic) response.

Again, element 1 is the critical element, with its DD consistently exceeding that of the TB reference model. EC8-93 leads to very poor performance of this element at small to moderate ρ_k values for all values of R. When the force reduction factor is large ($R = 5{\cdot}0$), the DD's of element 1 are excessively larger than those of the TB reference system, even for systems with large ρ_k values. NBCC-95 also results in poor performance of element 1 at small to moderate values of ρ_k when e is moderate ($e = 0{\cdot}2$) or large ($e = 0{\cdot}3$). It should be noted that when e is small ($e = 0{\cdot}1$), NBCC-95 does lead to satisfactory performance of element 1 (results are not shown). Among the three codes considered, UBC-94 is the most conservative for element 1, since it does not allow any reduction in strength (compared with the TB system) for this element, due to torsion. This provision leads to the lowest response of element 1 among the three codes considered and is generally conservative. UBC-94 is unconservative only when ρ_k is small and e is moderate to large, in which case the DD's of element 1 exceed marginally those of the TB reference system [Figures 10(c), (d)].

CONCLUSIONS

This study has addressed some issues which have been the subject of disputes in recent years when studying the seismic torsional response of TU buildings. It is important to resolve these issues before code torsional provisions can be evaluated appropriately. A better understanding of these issues also serves as the basis for developing an optimized design approach for lateral strength distribution in asymmetric buildings, which is the subject of the companion paper.[20] This study further evaluated the performance of code-designed TU buildings for both the serviceability and the ultimate limit states. The following conclusions may be drawn on the basis of the results obtained in this study.

1. The interpretation of the code ATP should be consistent with the analysis procedure. Including the full code ATP in determining the strength distributions in TU systems will lead to unconservative conclusions if accidental effects are not simulated in the analysis procedure. Since at the present stage, accidental effects cannot be fully simulated,[26, 27] and as a result are indeed generally not simulated in related analytical studies, two approaches, which are both consistent with the analysis procedure, have been employed in this study. One approach discounts the code ATP totally. The other allocates a part of the code ATP, equal to $0{\cdot}05b$, to account for all accidental effects and includes the remainder, if any, in the determination of strength distribution in TU models. This study has shown that results corresponding to these two approaches do not differ significantly for systems with moderate to large torsional stiffness. Significantly different results only occur when the system is torsionally flexible (low ρ_k). This study further concluded that despite the significantly different results for torsionally flexible systems, the two approaches still lead to the same conclusions with respect to the conservatism or otherwise unconservatism of code torsional provisions. On the basis of these conclusions, this paper recommends that the second approach be employed in future studies, since firstly it is consistent with the analysis procedure and secondly it can accommodate the view that the potential overconservatism in the code ATP can compensate for the possible unconservatism of the first term in the code design

eccentricity expressions. The latter advantage is particularly important when applying the torsional provisions of UBC-94, in which the low torsional stiffness of certain TU systems is taken into account by amplifying the code ATP, by a factor up to 3·0.

2. The performance of TU systems is governed by four primary system parameters, e, ρ_k, R, and T_y, the first two being the most critical. Currently, code torsional provisions have all considered the influence of e, some have considered the influence of ρ_k (explicitly in EC8-93 and implicitly in UBC-94 through the accidental eccentricity amplification factor A_x). The influence of R and T_y, although less critical compared with that of e and ρ_k, is significant and hence should also be taken into account in order to develop an improved, optimized design approach, which can ensure satisfactory performance of TU systems for both the serviceability and ultimate limit states.
3. The force reduction factor, R, influences the response of element 1 significantly. However, it has little effect on element 3. The displacement ductility ratio, Γ_{DD}, of element 1 increases with R. When R increases, namely when TU systems are excited increasingly into the inelastic range, TU systems respond increasingly like the TB reference system.
4. The uncoupled lateral period, T_y, also significantly influence the response of element 1. However, its influence on the response of element 3 is not significant. Γ_{DD} of element 1 in long-period TU systems is substantially larger than that in short period TU systems. On the other hand, Γ_{DD} of element 3 in long-period TU systems is slightly lower than that in short-period TU systems. Long-period TU systems respond more like the TB reference system than do short period TU systems.
5. The stiff edge element is the critical element for both limit states. In the case of the SLS, EC8-93 is unconservative and leads to poor performance of this element at small to moderate ρ_k, while UBC-94 and NBCC-95 are unconservative at small ρ_k for small to moderate e values. In the case of the ULS, EC8-93 again leads to poor performance of the stiff edge element. The degree of unconservatism and the range of ρ_k over which poor performance of this element occurs increase with the increase of R. When R is large ($R = 5$), EC8-93 results in very poor performance of this element over the full range of ρ_k. On the other hand, NBCC-95 is unconservative when ρ_k is small or moderate and when e is moderate or large. Among the three codes considered in this study, UBC-94 is the most conservative in estimating the strength demand of the stiff edge element. UBC-94 becomes slightly unconservative only when ρ_k is small and when e is moderate or large.
6. The flexible edge element is generally conservatively designed by all three codes for both limit states, except in the case of UBC-94 for the SLS design of short-period TU buildings, when e is small and ρ_k is moderate to large. In fact, codes are often overconservative. The degree of overconservatism increases with the decrease in ρ_k and with the increase in R and e. Hence, in general, too much strength has been allocated to the flexible edge element in accounting for the unfavourable effect of torsion.

ACKNOWLEDGEMENT

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